MOVPE growth and properties of [111]A−oriented piezoelectric InGaAs/GaAs/AlGaAs highly strained quantum well laser structures

Jongseok Kim [1)], Soohaeng Cho [1)], A. Majerfeld [1)], A. Sanz−Hervás [1)], G. Patriarche [2)], B. W. Kim [3)]

1) Department of Electrical and Computer Engineering, University of Colorado, Boulder, CO 80309−0425, U.S.A. , 2) Laboratoire de Photonique et de Nanostructures, CNRS−UPR 20, Route de Nozay, F−91460 Marcoussis, France , 3) Electronics and Telecommunications Research Institute, P.O. Box 106, Yusong, Taejon 305−600, Korea

Abstract

We report the properties of InGaAs/GaAs/AlGaAs double confinement strained quantum well (QW) structures embedded in P−I−N and N−I−P device configurations grown on (111)A GaAs substrates by MOVPE for application to laser diodes exploiting the piezoelectric field. The structural and optical properties of these structures were extensively analyzed by photoluminescence spectroscopy, high resolution X−ray diffractometry and transmission electron microscopy. From these analyses, it is shown that the strained QWs are pseudomorphic and their interfaces have less than ± 2 monolayers of roughness. The double confinement P−I−N QW structures with high interfacial quality led to the demonstration of piezoelectric [111]A strained InGaAs QW laser diodes operating at room temperature.

Introduction

Strained InGaAs/GaAs Quantum Well (QW) structures on <111>−oriented substrates have received considerable attention in the last few years because of potential advantages for device applications exploiting their special structural and physical properties which include a large piezoelectric (PE) field in the well [1].

Research on the growth, QW properties, and characteristics of optoelectronic devices with strained InGaAs/GaAs QW structures on <111>−oriented GaAs substrates has been reported mostly for [111]B−oriented structures grown by molecular beam epitaxy. Regarding metalorganic vapor phase epitaxy (MOVPE) grown structures, although MOVPE is the growth technique most widely used for production of III−V optoelectronic devices, there is only one report on a PE InGaAs/GaAs QW laser grown on a [211]B−oriented substrate, for which the PE field is smaller than in the <111> orientations [2]. Recently we reported the achievement of highly strained PE InGaAs/GaAs QW structures with excellent interfacial quality grown on (111)A GaAs substrates by MOVPE and their piezoelectric and pyroelectric properties [3−5].

In this paper we report the MOVPE growth and properties of PE strained QW laser structures on (111)A GaAs substrates. In order to obtain [111]A−oriented double confinement heterostructure lasers, the MOVPE growth of N− and P−type GaAs and AlGaAs layers on (111)A GaAs with high conductivity was developed, as well as the incorporation of PE QW structures. The InGaAs/GaAs/AlGaAs structures with 18−25 % In were grown on [111]A−oriented GaAs substrates in a P−I−N configuration to achieve lasers operating at ~1μm wavelength. The structures were extensively analyzed by photoluminescence (PL), high−resolution X−ray diffractometry (HRXRD), and transmission electron microscopy (TEM). Excellent interfacial properties (interface roughness ≤ ± 2 monolayers) for these PE strained QWs on doped AlGaAs layers were achieved. It will be shown also that the QWs are fully strained without any evidence of strain relaxation. Piezoelectric laser diodes operating at room temperature were fabricated using these high quality [111]A QW structures.

Experimental

Samples were grown by MOVPE in a horizontal quartz reactor operated at atmospheric pressure. Nominally exact [111]A−oriented N−type GaAs substrates were used. Trimethylindium (TMIn), Trimethylgallium (TMGa), Trimethylaluminum (TMAl), and 100% arsine (AsH_3) were used as sources. Silane and carbontetrachloride were used as the sources for the N and P dopants, respectively.

High−resolution X−ray diffractometry was used to analyze the crystal quality of the InGaAs/GaAs quantum well structures and to obtain their main structural values, such as InGaAs well and GaAs barrier widths, In fraction in the InGaAs well and the thickness and Al fraction in the AlGaAs cladding layers. For the PL measurements, an Ar+ laser with an excitation intensity of 2.5 W/cm^2 and a double pass monochromator were used. Low temperature PL measurements confirmed both the optical quality and interface quality of these structures. Cross−sectional TEM images were obtained under 002 dark field conditions for selected samples to examine the interfacial characteristics and the possible occurrence of misfit dislocations in the QWs.

Results and discussion

In order to make P−I−N or N−I−P double confinement QW laser structures we embedded single QW structures, the high interfacial quality of which was proven from analyses on undoped InGaAs/GaAs/AlGaAs structures [4], in a P−I−N or N−I−P configuration by incorporating doped GaAs and AlGaAs. From extensive layer doping studies, the appropriate MOVPE growth conditions were developed for N−type and P−type AlGaAs cladding layers and GaAs contact layers to obtain the required doping concentrations on the (111)A GaAs surface. Single QW structures on N−AlGaAs cladding layers were analyzed by PL in order to investigate the interfacial quality of the QW on doped layers. Photoluminescence spectra obtained at low temperature and room temperature (RT) for an InGaAs/GaAs QW with 22 % of In and a 70 Å well width are shown in Fig. 1. The RT PL wavelength is ~ 1μ m. The line width of the RT PL emission is apparently broad because of a shoulder peak. The shoulder peak is the result of weakly allowed optical transitions between the lowest confined electron state in the conduction band and the second confined state of the heavy hole valence band (E1−HH2), which is not allowed in conventional <100>−oriented structures. However, in this case, because of the existence of a piezoelectric field of ~170 kV/cm in the QW [5], the E1−HH2 transition is also observed. The 15K PL spectrum shows an apparently broad FWHM of 16 meV; however, due to the PE field in the well it corresponds to less than ±2 monolayers of actual interface roughness [6]. The high interfacial quality of [111]A QW structures embedded in P−I−N or N−I−P laser structures were confirmed further by HRXRD analyses and TEM observations. Figure 2 shows a TEM image of a QW structure with 18 % In embedded in an N−I−P configuration. The interface roughness is less than ±2 monolayers, which is similar to the result obtained from the PL analysis. We selected the P−I−N configuration for the laser structure because the direction of the piezoelectric field in the P−I−N configuration provides a potential profile which has advantages for our application. We fabricated laser diodes which had QW structures with similar interfacial characteristics and achieved piezoelectric laser diodes operating at room temperature. This is the first demonstration of [111] piezoelectric laser diodes fabricated by the MOVPE process.

Summary and conclusions

We developed InGaAs/GaAs/AlGaAs double confinement strained piezoelectric QW P−I−N and N−I−P structures on (111)A GaAs substrates by MOVPE for application to 1μm laser diodes. From PL, TEM and HRXRD analyses it is shown that the QW structures have heterointerfaces with less than ±2 monolayers of interface roughness. Laser diodes fabricated with a P−I−N double confinement QW structure operated at room temperature. The successful demonstration of this piezoelectric laser provides not only further evidence of the excellent properties of these highly strained InGaAs/GaAs/AlGaAs heterostructures grown on (111)A GaAs by MOVPE, but also indicates a good possibility for the realization of future devices exploiting the PE field in these type of structures.

Acknowledgment

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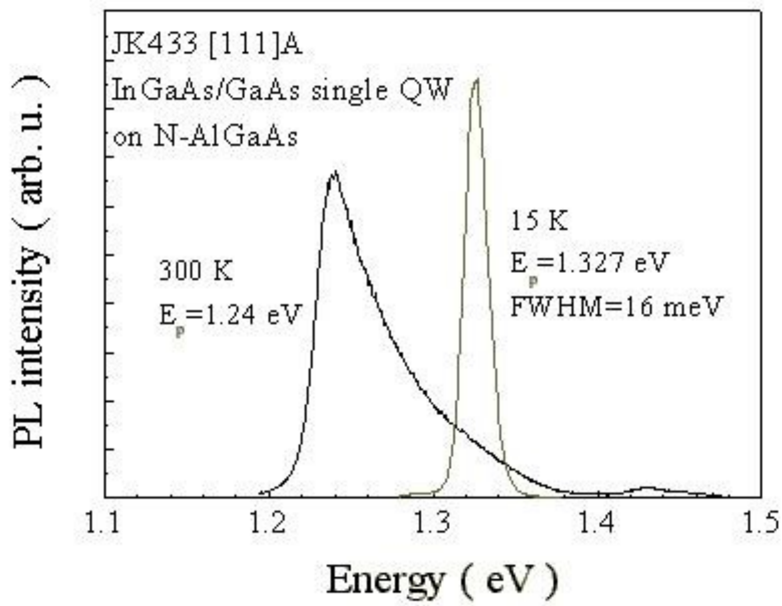

Fig. 1 Photoluminescence spectra obtained at 15K and room temperature for an InGaAs/GaAs single QW structure on an n−type AlGaAs cladding layer. E_p and FWHM denote the peak energy and full width at half maximum, respectively.

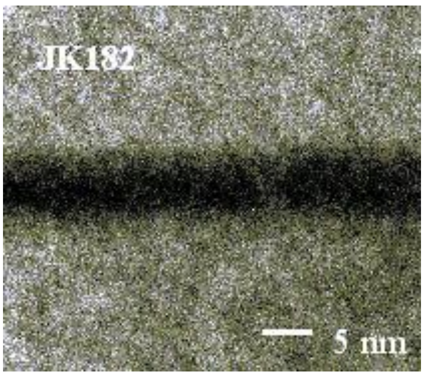

Fig. 2 Cross−sectional TEM image of an InGaAs/GaAs QW (well width: 58 Å; In content: 18 %) in an N−I−P laser structure